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Alternative-fuel-vehicle policy interactions increase U.S. greenhouse gas emissions

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ABSTRACT

The transportation sector is currently the largest contributor of greenhouse gas (GHG) emissions in the United States, and light-duty vehicles produce the majority of transportation emissions. Federal standards for fleet-averaged vehicle GHG emission rates and their corresponding corporate average fuel economy standards cap GHG emissions of the US light-duty vehicle fleet. In addition, two key policies aim to encourage a future fleet transition to alternative fuel vehicle (AFV) technologies: (1) incentives that treat AFVs favorably in the federal GHG standard, and (2) state zero-emissions vehicle (ZEV) policy, which mandates AFV sales in some states. While each of these AFV policies can encourage AFV adoption, we show that net GHG emissions increase when both policies are present simultaneously. Specifically, we estimate changes in life cycle GHG emissions and gasoline consumption, relative to a pure federal fleet GHG standard (without AFV incentives or mandates), resulting from the introduction of (1) AFV incentives in federal fleet GHG policy, (2) state ZEV mandates, and (3) the combination of the two. We find that under fairly general conditions the combined AFV policies produce higher GHG emissions than either policy alone. This result is a consequence of state mandates increasing AFV sales in the presence of federal incentives that relax the fleet GHG standard when AFVs are sold. Using AFV sales projections from the Energy Information Administration and the California Air Resources Board, we estimate that the combined policies produce an increase on the order of 100 million tons of CO_2 emissions cumulatively for new passenger cars sold from 2012 through 2025 relative to a pure GHG standard. AFV incentives in the GHG standard conflate policy goals by encouraging AFV adoption at the cost of higher fleet GHG emissions, and they permit even higher fleet GHG emissions when other policies, such as the ZEV mandate, increase AFV adoption.

1. Introduction

Federal light-duty fleet greenhouse gas (GHG) emission standards and associated Corporate Average Fuel Economy (CAFE) standards cap average vehicle emission rates in the U.S. Additionally, to encourage a long term transition to technologies capable of operating with near-zero emissions, federal and state policies encourage automakers to sell alternative-fuel vehicles (AFVs) – vehicles that can operate on fuels other than gasoline and diesel. AFVs include (1) dual-fuel vehicles, such as flex-fuel vehicles (FFVs) and plug-in hybrid electric vehicles (PHEVs), and (2) single-fuel vehicles, such as battery electric vehicles (BEVs) and fuel cell vehicles (FCV). Two important policies intended to encourage AFV adoption are:

1. **AFVIs:** Incentives in federal light-duty vehicle GHG emission standards for automakers that sell AFVs count AFVs favorably in compliance calculations. We refer to these AFV incentives as AFVIs.
2. **ZEV:** California and nine other states mandate AFV sales under state zero emission vehicle (ZEV) policy. These states represented approximately 35% of the U.S. new vehicle market in 2017. The ZEV policy requires large automakers that sell vehicles in the state to sell low- and zero-tailpipe-emission vehicles (primarily AFVs) as a prescribed portion of their state fleet sales.

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We examine the individual and combined effect of these federal and state policies that promote AFVs on fleet GHG emissions and gasoline consumption. We first review federal automotive CAFE/GHG policy, state ZEV policy, and relevant literature; we then develop a model of fleet emissions and gasoline consumption and apply it to policy scenarios involving CAFE/GHG policy both with and without AFVI and ZEV policies under a range of assumptions; we identify a set of sufficient conditions under which our key findings hold; and finally, we discuss the implications of our findings.

1.1. Federal corporate average fuel economy standards and greenhouse gas emission standards

CAFE standards were first implemented in the Energy Policy Conservation Act of 1975 to increase vehicle fuel efficiency and reduce reliance on foreign oil, following the 1973 oil crisis[1]. Since their inception, the standards have been implemented by the National Highway Traffic Safety Administration (NHTSA) in the Department of Transportation (DOT). The standards require manufacturers to meet sales-weighted average fuel efficiency targets for each model year sold, with separate standards for passenger vehicles and light-duty trucks. The initial set of standards came into effect in 1978 for passenger cars and 1979 for light-duty trucks (Fig. 1). Over time, the stringency of the standards was increased. By 1990, the passenger car standards were set at 27.5 miles per gallon (MPG), as measured using a 2-cycle laboratory test. Seven years later, the light-duty truck standards were also increased to 20.7 MPG. In 2012, the standards were modified to a footprint-based standard,[2] where automakers that sell smaller cars have higher fuel efficiency targets. In addition, due to a court ruling in 2007[3] that required the Environmental Protection Agency (EPA) to regulate carbon dioxide as a pollutant, the EPA wrote a new set of fleet GHG standards that were harmonized with the NHTSA CAFE standards in order to have comparable stringency (GHG emissions are proportional to gasoline consumption).[4,5] The newest set of standards is for model years 2017 through 2025, with NHTSA regulating fuel efficiency (MPG) and EPA regulating equivalent carbon dioxide emission rates (grams of CO_2 per mile). The Trump administration has proposed a revised set of standards with reduced stringency for model years 2022–2026.[6]

The current set of CAFE and GHG rules each contain a provision establishing a set of incentives for automakers to sell AFVs. The CAFE AFV incentives are longstanding and set by statute, including a factor for converting alternative fuel consumption into a gasoline equivalent when assessing compliance. The incentives in the GHG rule include multipliers and weighting factors set by EPA. A multiplier allows each AFV sale to count in compliance calculations as though it were multiple sales. A weighting factor treats AFV emissions in compliance calculations as though they are lower than they actually are. Both incentives relax the GHG requirement for an automaker's fleet (Jenn et al., 2016). The full list of AFV incentives are summarized in Table S1 of the Supplementary Information (SI). For dual-fuel vehicles, EPA determines the portion of vehicle miles traveled assumed to be propelled by the alternative fuel, and we adopt their estimates.

The EPA released reports in 2010 and in 2012 evaluating the 2012–2016 and 2017–2025 CAFE standards, respectively. They estimate that the fuel efficiency standards are expected to cumulatively reduce CO_2 emissions by 960 million metric tons for model years 2012–2016 and 2 billion metric tons for model years 2017 through 2025 over the lifetime of the vehicles.[7,8]

Independent researchers have estimated emissions savings due to CAFE/GHG policy using a variety of methods and arrived at reasonably consistent estimates: Using various equilibrium frameworks, Morrow et al. (2010) estimate reductions on the order of 1.2–1.6 billion metric tons of CO_2 for vehicles in operation from 2010 through 2030 (extending CAFE through 2030); Karplus and Paltsev (2012), using a general equilibrium approach, estimate a cumulative savings of 2.7 billion metric tons of CO_2 over the lifetime of vehicles sold from 2012 through 2025; Sarica and Tyler (2012), using a hybrid MARKAL model, estimate reductions of 150–200 million metric tons of CO_2 annually by 2030; and O'Rear et al. (2015), also using MARKAL, estimate savings of 10.5% in CO_2 emissions resulting from CAFE in 2025 relative to stagnant standards. Bastani et al. (2012) use expert elicitation and estimate an annual decrease of 300 million tons of CO_2 (with 95% confidence intervals of 100–450 million tons) in 2025 compared to 2008.[9,10,11]

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[1] Energy Policy and Conservation Act, 1975. Public Law. 94163. United States Congress.

[2] A vehicle footprint measures the area resulting from the product of the wheelbase and track length of the vehicle. The intent of the footprint-based standard is to put pressure on all vehicles to reduce fuel efficiency via technology, rather than pushing consumers into smaller vehicles.

[3] *Massachusetts v. Environmental Protection Agency*, 127 S. Ct. 1438, 549 U.S. 497, 167 L. Ed. 2d 248 (2007).

[4] Federal Register Vol. 75, No. 88: Light-Duty Vehicle Greenhouse Gas Emissions Standards and Corporate Average Fuel Economy Standards; Final Rule.

[5] Federal Register Vol. 77, No. 199: 201 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards.

[6] Federal Register Vol. 83, No. 165, pp 42986–43500 "The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021–2026 Passenger Cars and Light Trucks", Notice of Proposed Rulemaking, August 2018.

[7] US EPA Regulatory Announcement. "EPA and NHTSA Finalize Historic National Program to Reduce Greenhouse Gases and Improve Fuel Economy for Cars and Trucks". Office of Transportation and Air Quality, EPA-420-F-10-014. April 2010.

[8] US EPA Regulatory Announcement. "EPA and NHTSA Set Standards to Reduce Greenhouse Gases and Improve Fuel Economy for Model Years 2017–2025 Cars and Light Trucks". Office of Transportation and Air Quality, EPA-420-F-12-051. August 2012.

[9] US EPA Regulatory Announcement. "EPA and NHTSA Finalize Historic National Program to Reduce Greenhouse Gases and Improve Fuel Economy for Cars and Trucks". Office of Transportation and Air Quality, EPA-420-F-10-014. April 2010.

[10] US EPA Regulatory Announcement. "EPA and NHTSA Set Standards to Reduce Greenhouse Gases and Improve Fuel Economy for Model Years 2017–2025 Cars and Light Trucks". Office of Transportation and Air Quality, EPA-420-F-12-051. August 2012.

[11] US EPA Regulatory Announcement. "EPA and NHTSA Set Standards to Reduce Greenhouse Gases and Improve Fuel Economy for Model Years 2017–2025 Cars and Light Trucks". Office of Transportation and Air Quality, EPA-420-F-12-051. August 2012.

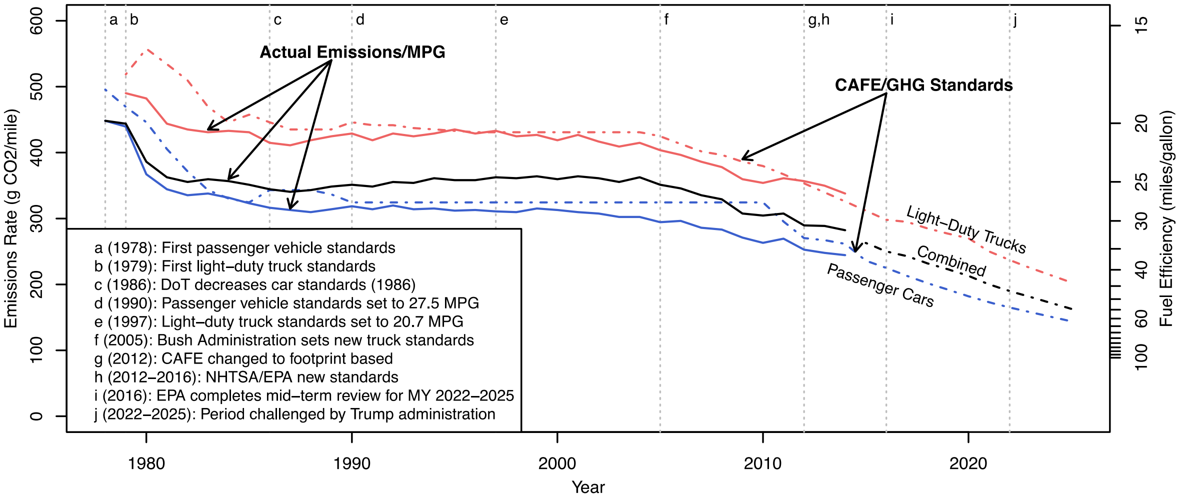

Fig. 1. Historical and Expected CAFE Standards from 1978 to 2025 (and harmonized GHG standards from 2012 to 2025). The years in parentheses correspond to the year the policy was first implemented. Each dotted line refers to the corresponding policy standard in that year, and each solid line refers to the actual values observed in the market. Beginning in 2012 the fleet standard depends on the mix of vehicles sold (specifically size (footprint)), and the overall sales-weighted averages shown beyond 2014 are therefore based on projections of vehicle footprint sales mix. (Office of Transportation and Air Quality. *EPA and NHTSA Finalize Historic National Program to Reduce Greenhouse Gases and Improve Fuel Economy for Cars and Trucks*. EPA-420-F-10-014. April 2010. Office of Transportation and Air Quality. *EPA and NHTSA Set Standards to Reduce Greenhouse Gases and Improve Fuel Economy for Model Years 2017–2025 Cars and Light Trucks*. EPA-420-F-12-051. August 2012. Hicks, Maurice. U.S. Department of Transportation. *Summary of Fuel Economy Performance*. December 15, 2014).

Though the GHG standards reduce emissions, economists have repeatedly raised concerns that they do so inefficiently and have a variety of other implications. Standards that increase vehicle efficiency also reduce the marginal cost of driving and may encourage additional vehicle miles traveled, with corresponding fuel consumption, emissions, congestion, and accidents (Linn, 2016; Parry et al., 2007), and they may result in reduced vehicle weight, affecting collision fatality rates (Jacobsen, 2013a,b; Anderson and Auffhammer, 2013). The standards also affect the used car market, which can incentivize consumers to keep old cars longer and can have a regressive effect (Jacobsen and Benthem, 2015; Jacobsen, 2013a,b; Davis and Knittel, 2016). A key justification for fuel economy policy is that consumers may undervalue future fuel savings when purchasing a vehicle and thus benefit if fleet efficiency improves, but the evidence for this is mixed (e.g.: (Allcott and Wozny, 2014; Busse et al., 2013). Economists overwhelmingly view fuel taxes and mileage taxes as more efficient policies (Parry et al., 2007); however, the presence of other policies can change the relative advantages of alternative policy instruments (Goulder et al., 1999), and when regulations have incomplete scope or jurisdiction, enabling leakage of emissions from the regulated domain to the unregulated domain, it is possible for intensity standards to be more efficient than an emissions tax (Holland, 2012).

One important type of leakage can occur when state policies interact with federal policy. The federal fleet standard must be satisfied overall regardless of what vehicles are sold in a particular state, so sale of efficient or alternative fuel vehicles in one state may have no net impact on fleet emissions when the CAFE/GHG standard acts as a binding constraint. Goulder and Stavins (2011) and Goulder et al. (2012) note that California efforts to increase fleet fuel efficiency within the state lead to "leakage" where emissions gains in California are offset when higher-emitting vehicles sold in the rest of the U.S. take up the slack in the CAFE/GHG standard. A Congressional Budget Office report also notes this in the context of electric vehicles, stating that under a CAFE regime, electric vehicle sales produce no near-term change in the fleet emission rate (Gecan, 2012) (though they may have long term impact if innovation or adoption of these vehicles leads to most stringent future standards). In addition to the leakage effect, Jenn et al. (2016) argue that because AFV incentives in CAFE/GHG policy loosen the standards whenever AFVs are sold, the net near-term result of increasing AFV adoption in place of conventional vehicles is an increase in fleet emissions and fuel consumption. The EPA identifies this effect in their final rule and states that "To facilitate market penetration of the most advanced vehicle technologies as rapidly as possible, EPA is proposing an incentive multiplier for compliance purposes for all electric vehicles (EVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell vehicles (FCVs)"; "advanced technology vehicle multipliers … are expected to have an impact on the fleet-wide emissions levels that manufacturers will actually achieve"; and "EPA believes it is worthwhile to forego modest additional emissions reductions in the near term in order to lay the foundation for the potential for much larger 'game-changing' GHG emissions and oil reductions in the longer term."[12] We estimate the near-term increase in GHG emissions in the context of ZEV policy and compare the effect of the policies independently and jointly.

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[12] p. 74869 and 74878, Federal Register Vol. 77, No. 199: 201 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards.

1.2. State zero emission vehicle programs

The ZEV requirements were originally established in 1990 as part of California's Low-Emission Vehicle regulation by CARB. The ZEV program is intended to induce a change in the technology composition of the vehicle fleet by creating a market for AFV technologies. The program works by requiring that a minimum portion of the fleet sold by each of the larger automakers in the state each year are ZEVs. It is now viewed as an important part of the strategy to help achieve California's goal (established in California Assembly Bill (AB) 32[13] and AB 1493[14]) to reduce the state's GHG emissions to 1990 levels by 2020 in the face of increasing vehicle usage by establishing a market for vehicle technologies capable of producing near-zero operation-related emissions (given an appropriate fuel source and production pathway). This requirement was followed by an ambitious goal to reduce emissions to 80% of 1990 levels by 2050 (Footnote 13). Tables S2 and S3 in the SI summarizes requirements for ZEV sales as a percentage of total sales in California. The 1990 and 1996 plans were both changed before their implementation in 1998 and 2003, respectively. The 2001 plan faced litigation[15] in state lawsuits for linking ZEV credits to fuel efficiency metrics, during which an injunction was issued that prevented CARB from enforcing ZEV mandates in 2003 and 2004.

CARB amended the ZEV requirements in 2003, requiring manufacturers to sell 2% pure ZEVs (BEVs or FCVs), 2% advanced technology partial-ZEVs (AT-PZEVs, which include PHEVs and hybrid electric vehicles (HEVs)), and 6% partial ZEVs (PZEVs, which are fuel efficient conventional vehicles) starting in 2005. However, manufacturers were given an alternative path of compliance, allowing AT-PZEVs to meet the ZEV requirements as long as the manufacturer sold 250 hydrogen FCVs through 2008 and 2500 FCVs in 2009 through 2011. In addition, only manufacturers selling more than 60,000 vehicles annually in the state of California are required to meet the full ZEV compliance mandate (the five manufacturers are Ford, GM, Honda, Nissan, and Toyota[16]). The alternative compliance path has allowed manufacturers to meet the ZEV requirements without a drastic change in their sales. The current iteration of ZEV policy is the 2012 plan,[17] which has since undergone a midterm review in 2017[18] requiring sales of four vehicle categories: ZEVs (FCVs and BEVs), transitional partial-ZEVs (TZEVs: PHEVs and dual-fuel FCVs), AT-PZEVs (HEVs, compressed natural gas vehicles (CNGVs), and methanol FCVs), and PZEVs (extremely clean conventional vehicles).

Because California's air quality standards preceded the federal Clean Air Act of 1970, California retained authority to regulate its own emissions, and other states are permitted to adopt its standards under Section 177 of the Clean Air Act (this authority is being challenged by the Trump administration) (Footnote 6). Several other states that adopted California's ambient air quality standards also elected to regulate sales of their vehicles under the ZEV policy. These states are Connecticut, Maryland, Massachusetts, New York, Rhode Island, Vermont, Oregon, Maine, and New Jersey.[19]

The Zero Emission Vehicle mandate in California has been in place for over two decades under several different plans. Brown et al. (1995) provide an early perspective overview on the regulation and the role of command-and-control policies. Many of the issues described, such as emissions reductions, free market efficiency, and public support, remain issues of active discussion for AFVs today. Collantes and Sperling (2008) provide a review of ZEV policy origins and history, drawing on discussion with policy founders and stakeholders and identifying motivations for how and why various aspects of ZEV policy were constructed. Sperling and Eggert (2014) argue that ZEV accomplishes a necessary role in the transportation sector to meet California's aggressive energy and climate targets for 2030 and beyond, in part because market mechanisms, such as carbon taxes or cap-and-trade programs, face huge political resistance and fail to address a number of market failures. While automakers resisted ZEV policy, Wesseling et al. (2014, 2015) observe an industry transition from defensive toward acceptance and eventual proactive support for the socio-technical change. ZEV policy has been estimated to result in a reduction of 470,000 tons of CO_2 reduced in the Bay Area, due to EV deployment, by 2020 (Witt et al., 2012) and 50 million tons of CO_2 avoided total by 2025 (Cunningham, 2010). We show that despite potential local changes, in the presence of a binding fleet GHG standard with AFV incentives, ZEV policy results in increased net U.S. emissions.

1.3. Other alternative fuel vehicle policies

There are a number of other policies, both incentives and regulations, that help promote the adoption of AFVs. For example, both Renewable Fuel Standards and Low Carbon Fuel Standards aim to lower the total carbon intensity of transportation fuels by promoting alternative energy and fuels such as ethanol, compressed natural gas, and electricity. Additionally, there are various federal, state, and local incentives for AFVs, including monetary (e.g., tax credits or rebates such as the Plug-In Electric Drive Vehicle Credit) and non-monetary incentives (e.g., access to carpool lanes). Because incentives in CAFE/GHG policy allow automakers that sell alternative fuel vehicles to meet less stringent fleet standards, policies that increase AFV sales can interact with federal CAFE/GHG

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[13] Assem. Bill 32, 2005–2006 Reg. Sess. (Cal. 2006) www.leginfo.ca.gov/pub/05-06/bill/asm/ab_0001-0050/ab_32_bill_20060927_chaptered.pdf.

[14] Assem. Bill 1493, 2002–2003 Reg. Sess. (Cal. 2002). www.arb.ca.gov/cc/ccms/documents/ab1493.pdf.

[15] *Central Valley Chrysler-Plymouth, Inc., et al. v. Witherspoon*, Case No. CIV F-02-05017 REC SMS (E.D. Cal.); *Liberty Motors, Inc., et al. v. California Air Resources Board, et al.*, Case No. 02 CE CG 00039 (Superior Court for Fresno County); *Daimler Chrysler Corp. et al. v. California Air Resources Board et al.*, Case No. 02 CE CG 04456 HAC (Superior Court for Fresno County).

[16] California Environmental Protection Agency, Air Resources Board: Fact Sheet. http://www.arb.ca.gov/msprog/factsheets/2003zevchanges.pdf.

[17] California Air Resources Board. *Zero-Emission Vehicle Standards for 2009 through 2017 Model Year Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicles*, S. 1962.1: https://www.arb.ca.gov/msprog/zevprog/zevregs/1962.1_Clean.pdf.

[18] California Air Resources Board. *California's Advanced Clean Cars Midterm Review:* https://www.arb.ca.gov/msprog/acc/mtr/acc_mtr_finalreport_full.pdf.

[19] ZEV Program, Center for Climate and Energy Solutions. http://www.c2es.org/us-states-regions/policy-maps/zev-program.

	No ZEV Policy	ZEV Policy
No AFV Incentives in the GHG Standard	REF scenario	ZEV scenario
AFV Incentives in the GHG Standard	AFVI scenario	BOTH scenario

Fig. 2. Illustration of policy scenarios.

policy to produce increased U.S. emissions (Jenn et al., 2016). We focus here on the interaction of federal GHG policy with state ZEV policy.

2. Model

To examine the interaction of state ZEV policy with federal AFV incentives in the GHG standard, we compare life cycle fleet GHG emissions (tons of CO_2-equivalent) and gasoline consumption (gallons of gasoline) under four policy scenarios, summarized in Fig. 2.

We first derive expressions for fleet GHG emissions and gasoline consumption by building on the framework of Jenn et al (2016) and extending it to capture life cycle emissions in real-world driving conditions when agency emissions estimates may differ from real world emissions. We then apply these expressions to the four scenarios of Fig. 2, compute differences, and analyze results in two ways: (1) we conduct simulations using a range of assumptions for the input parameters and (2) we identify a general set of conditions under which emissions are higher in the "BOTH" scenario than in the other scenarios. Automakers must comply with both the light-duty GHG standard, enforced by the EPA, and the CAFE standard, enforced by NHTSA. The two standards are harmonized to be similar, but they have some differences due, in part, to differences in regulatory authority. We treat the light-duty fleet GHG standard as the binding federal standard because the penalty for violating the nearly-equivalent CAFE standard is relatively mild, whereas the penalty for violating the GHG standard is potentially severe (revocation of the license to sell vehicles) (Jenn et al., 2016). We assume automakers overall design and price their fleets in order to exactly satisfy the federal fleet GHG constraint each year in all scenarios. We ignore the potential for automakers to bank GHG credits, as permitted in federal policy, so we expect our estimates to be optimistic, since a strategic firm might bank GHG credits in years where AFV incentives are large and then spend those credits in future years when incentives decline. Such behavior would result in larger GHG increases than we model here.

We investigate the emissions implications of the ZEV, AFVI, and BOTH scenarios relative to the REF scenario due to projected changes in the sales of AFVs as well as their associated effects on the conventional fleet. In each scenario, we aim to model real-world emissions, taking into account (1) the difference between the 2-cycle laboratory tests used for CAFE/GHG compliance calculations and the 5-cycle laboratory tests that better approximate on-road conditions, (2) upstream emissions from electric vehicle charging and potential for agency error in estimating those emissions, and (3) life-cycle emissions from vehicle production.

2.1. Fleet GHG emissions

We model life cycle emissions (including use-phase emissions and vehicle production emissions) from the U.S. light-duty vehicle fleet as

$$E = \nu\left(\sum_{j\in J_{\mathrm{C}}} n_j r_j^{\mathrm{G}} + \sum_{j\in J_{\mathrm{A}}} n_j\left(p_j r_j^{\mathrm{A}} + (1-p_j) r_j^{\mathrm{G}}\right)\right) + \sum_{j\in J} n_j \gamma_j \tag{1}$$

where total life cycle GHG emissions E are composed of emissions associated with gasoline vehicle operations, alternative fuel vehicle operations, and vehicle production, respectively. Specifically, J_{C} is the set of conventional vehicle designs, J_{A} is the set of AFV designs (including dual fuel vehicles), $J = J_{\mathrm{C}} \cup J_{\mathrm{A}}$ is the set of all vehicle designs, ν is the lifetime distance traveled per vehicle (assumed equal for all vehicles),[20] n_j is the number of units of vehicle j sold, r_j^{G} is the GHG emissions rate of vehicle j when operating on gasoline/diesel (including upstream emissions for fuel production and distribution), r_j^{A} is the GHG emissions rate of vehicle j when operating on its alternative fuel (including upstream emissions for fuel production and distribution), p_j is the portion of vehicle miles traveled for which vehicle j is propelled by the alternative fuel ($p_j = 0$ for pure AFVs, $p_j = 1$ for conventional gasoline vehicles, and $0 < p_j < 1$ for dual fuel vehicles), and γ_j is the total GHG emissions associated with manufacturing one unit of vehicle j.

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[20] Any significant systematic differences in VMT among vehicle types could further modify results.

2.1.1. *Accounting emissions*

For each manufacturer, the EPA sets an emission standard $\bar{s}$ based on the size (footprint) of the manufacturer's vehicles and requires the manufacturer's modified sales-weighted fleet emission rate to be at or below the standard:

$$\frac{\sum_{j\in J_{\mathrm{C}}} n_j\tilde{r}_j^{\mathrm{G}} + \sum_{j\in J_{\mathrm{A}}}(n_j m_j(p_j\tilde{r}_j^{\mathrm{A}}w_j + (1-p_j)\tilde{r}_j^{\mathrm{G}}))}{N + \sum_{j\in J_{\mathrm{A}}} n_j(m_j-1)} \leqslant \bar{s} \tag{2}$$

where the emissions rate of each gasoline and alternative fuel vehicle is weighted by its respective sales, added together, and divided by total sales, after making modifications for AFV incentives. Specifically, the AFV incentives artificially reduce the emissions of AFVs when operating on an alternative fuel by the weighting factor w and artificially increase the number of AFVs sold by the multiplier m. Here w is the AFV incentive weighting factor, m is the AFV incentive multiplier, $N = \sum_{j\in J_{\mathrm{C}}} n_j + \sum_{j\in J_{\mathrm{A}}} n_j$ is the total number of vehicles sold, and the tilde symbol $(\sim)$ denotes emissions as measured by the 2-cycle laboratory regulation compliance procedure (which differs from on-road emission rates). When $w = m = 1$, Eq. (2) corresponds to the pure GHG standard (top row of Fig. 2). Table S1 in the SI summarizes the schedule of AFV incentives in the existing standard. The AFV incentives allow automakers to effectively meet a less stringent standard than they would have been able to otherwise (Jenn et al., 2016), and we provide an additional discussion in the SI. Compliance credits can be traded among automakers so that some automakers can over-comply with Eq. (2) and earn credits while other automakers under-comply with Eq. (2) and must buy credits from others. When the industry as a whole complies exactly with the regulation the inequality in Eq. (2) becomes an equality.

2.1.2. *On-road emissions*

If the true on-road emission rate of each vehicle is δ times as large as measured by the regulation's 2-cycle laboratory test, and if the AFVs have an additional factor c to account for the potential difference between the real-world emission rate for upstream emissions of the alternative fuel (e.g.: electricity production emissions) relative to the emission rate used in policy compliance calculations,[21] then:

$$r_j^{\mathrm{G}} = \delta\tilde{r}_j^{\mathrm{G}} \tag{3}$$

$$r_j^{\mathrm{A}} = \delta(\tilde{r}_j^{\mathrm{A}} + c_j) \tag{4}$$

If we solve Eq. (2) as an equality for $\sum_{j\in J_{\mathrm{C}}} n_i r_j^{\mathrm{G}}$ and substitute it together with Eqs. (3) and (4) into Eq. (1), we obtain:

$$E = \delta\nu\left(\bar{s}\sum_{j\in J} n_j + \sum_{j\in J_{\mathrm{A}}} n_j p_j c_j + \sum_{j\in J_{\mathrm{A}}} n_j(p_j\tilde{r}_j^{\mathrm{A}}(1-m_j w_j) + (m_j-1)(\bar{s}-(1-p_j)\tilde{r}_j^{\mathrm{G}}))\right) + \sum_{j\in J} n_j\gamma_j \tag{5}$$

Here the first term inside the parentheses represents the fleet emissions implied by the value of the standard itself; the second term represents additional upstream emissions for AFVs correcting for agency measurement error; the third term represents the increase in permitted fleet emissions due to AFV incentives (if $m = w = 1$, this term is zero); and the last term represents emissions from vehicle manufacturing. The emissions rate r_j^{G} for gasoline vehicles J_{G} does not appear because it is determined implicitly, together with sales volumes, to satisfy the binding fleet GHG standard in Eq. (2) as an equality. Thus, our analysis is agnostic about the degree to which the slack in the fleet GHG standards is absorbed by (1) redesign of the vehicles and (2) shift of sales mix (e.g.: through re-pricing or promotion).

2.2. *Fleet gasoline consumption*

Fleet gasoline consumption can be calculated by dividing the portion of GHG emissions associated with gasoline consumption by the rate of carbon dioxide emissions associated with burning gasoline τ.[22]

$$G = \frac{\nu\left(\sum_{j\in J_{\mathrm{C}}} n_j r_j^{\mathrm{G}} + \sum_{j\in J_{\mathrm{A}}} n_j(1-p_j)r_j^{\mathrm{G}}\right)}{\tau} \tag{6}$$

Following a similar procedure, the fleet gasoline consumption G is therefore:

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[21] Technically, the emission rate for gasoline vehicles used in compliance calculations counts only combustion emissions, and the (upstream) emission rate used for alternative fuel vehicles is adjusted relative to the upstream emission rate of gasoline vehicles, but we ignore differences between these accounting approaches in our model. See Jenn et al. (2016) and Federal Register v77 n199 p62822 for more details.

[22] We use an EPA value of 11,200 g of CO_2/gallon of gasoline (https://www.epa.gov/sites/production/files/2016-07/documents/select-ghg-results-table-v1.pdf), which includes both combustion emissions and upstream emissions related to the production of fuel (drilling, refining, and transport). We ignore diesel vehicles, since they make up a small fraction of U.S. passenger cars. We also ignore gasoline consumption in the production of vehicles and fuels.

$$G = \frac{\nu\delta}{\tau}\left(\bar{s}N - \sum_{j\in J_{\mathrm{A}}} n_j p_j \widetilde{r}_j^{\mathrm{A}} w_j + \sum_{j\in J_{\mathrm{A}}} (n_j(m_j - 1)(\bar{s} - p_j \widetilde{r}_j^{\mathrm{A}} w_j - (1 - p_j)\widetilde{r}_j^{\mathrm{G}}))\right) \tag{7}$$

Here the first term inside the parentheses represents operation GHG emissions implied by the pure standard, the second term removes the weighted portion of those emissions from AFVs that are not caused by gasoline combustion (the weight w accounts for increases in the conventional fleet due to the weighting incentive alone), and the third term represents additional permitted GHG emissions from the gasoline fleet due to combined weights and multipliers (if $m = 1$, this term is zero). The term τ converts these gasoline-related GHG emissions into gallons of gasoline consumed.

In the following sections we first conduct simulations by computing Eqs. (5) and (7) for the scenarios in Fig. 2 using a variety of assumptions for input parameters and reporting the difference between each of the ZEV, AFVI, and BOTH scenarios and the REF scenario. We then identify a set of conditions under which Eq. (5) is larger in the BOTH scenario than it is in the other scenarios.

3. Simulation

3.1. Assumptions

To determine emissions and gasoline consumption for the fleet in the four scenarios, we need to know the following quantities for each scenario: the fleet's GHG standard $\bar{s}$, lifetime miles traveled per vehicle ν, the fleet's total sales volume $\sum_{j\in J} n_j$, the production emissions of each vehicle model γ_j, and the ratio of on-road energy consumption to 2-cycle laboratory test cycle energy consumption δ. Additionally, for each AFV model we need to know the sales volume $n_j\ \forall\ j \in J_{\mathrm{A}}$, the emission rate when operating on its alternative fuel $r_j^{\mathrm{A}\prime}$ and when operating on gasoline $r_j^{\mathrm{G}\prime}$ (where applicable), the proportion of vehicle miles traveled operating on the alternative fuel p_j, and the difference between the real-world upstream emission rate of the alternative fuel and the value used for policy compliance calculations, c_j. We estimate each of these quantities in turn, focusing on the passenger car market because ZEV regulation has affected primarily this market. If some scenarios induce other changes, such as a change in the fleet's sales-weighted vehicle footprint or vehicle miles traveled, there could be additional effects beyond those modeled here.

3.1.1. Vehicle sales projections

As a base case, our results use passenger car sales projections modified from the Energy Information Administration's 2015 Annual Energy Outlook (AEO) projections through 2025. Vehicle technologies from the AEO projection include conventional vehicles, FFVs, BEVs, PHEVs, CNGVs, and FCVs. The cumulative sales projections of major AFVs for our base case are summarized in the SI. We examine a range of alternative projections in the SI and find similar qualitative conclusions.

The AEO sales projections are made assuming the presence of CAFE/GHG and ZEV policy, and they attribute a portion of projected sales to ZEV policy. For our ZEV scenarios we adopt the AEO projections. For our non-ZEV scenarios, the assumed sales volume for each AFV is modified from the original AEO sales projection (with ZEV) to remove the sales attributed to ZEV policy. The AEO provides an overall estimate of AFV sales attributed to ZEV policy, but it does not provide a breakdown for each AFV type, so we proportionally allocate the projections among all vehicle technologies, as described in the SI. In all cases the total of all fleet sales is held constant, and any changes to sales of AFVs are offset by sales to conventional vehicles (we examine alternative assumptions in the SI). We estimate E from equation and G from equation for each scenario in Fig. 2 and report differences across scenarios.

Our work is not intended to model the vehicle market and produce forecasts of vehicle technology adoption. Instead, we include a sensitivity analysis that encompasses a wide range of plausible AFV adoption outcomes including forecasts based on the EIA's Annual Energy Outlook as well as alternative forecasts based on CARB projections and modified "no ZEV mandate" scenarios using historical sales for attribution as an alternative to AEO's attribution of ZEV sales. These alternative data inputs and corresponding results are discussed in the supplemental information, and we discuss robustness of our findings in the results section.

3.1.2. Vehicle attribute inputs

Emission rates and the proportion of vehicle miles traveled driven on alternative fuels used in EPA compliance calculations are obtained from literature (National Center for Statistics and Analysis, 2006) and the EPA's fuel economy data.[23] For vehicle production emissions, we focus on differences among technologies, since the portion of production emissions common across all vehicle alternatives cancels out in all cases ($\gamma_j = \gamma + \gamma_j'$ where γ is the portion of emissions common across all technologies and γ_j' is the portion specific to product j). In our numerical simulations we therefore ignore γ, and we assume the only non-negligible technology difference for production emissions γ_j' is the emissions associated with the production of batteries for plug-in electric vehicles. The values used for γ_j' for electric vehicles are formed by the high and low values found in the literature for battery production (Table S5). We use the NHTSA's technical documentation on vehicle survivability and travel mileage schedules as the basis of the average lifetime miles traveled over the lifetime of the vehicle, totaling 150,000 miles (National Center for Statistics and Analysis, 2006).

3.1.3. On-road performance

We estimate the ratio δ by obtaining the median of the factor increase from 2-cycle emission rates to 5-cycle emission rates for

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[23] US Department of Energy and US Environmental Protection Agency, *Fuel Economy Datafiles*. https://www.fueleconomy.gov/feg/download.shtml.

every vehicle listed in the 2015 EPA Fuel Economy Datafile (Footnote 23), which yields $\delta = 1.31$. The sensitivity analysis encompasses the minimum factor increase of $\delta = 1.17$ and the maximum factor increase of $\delta = 1.51$ with no major categorical average difference between conventional vehicles and electric vehicles (the only AFVs with sufficient data to compute an average δ). No existing vehicle model in the 2015 Fuel Economy Datafile has a lower factor increase than 1.17 or a higher factor increase than 1.51. The location-related marginal emission factors for electric vehicles is important to accurately assess emissions from electric vehicles, and we adopt a range of estimates for regional marginal electricity grid emission factors summarized in Table S8 in the SI, wide enough to capture estimates from multiple studies, regions, seasons, and charge timing assumptions (Holland, Mansur, Muller, and Yates, 2016; Zivin, Kotchen, and Mansur, 2014; Tamayao, Michalek, Hendrickson, and Azevedo, 2015; Yuksel, Tamayao, Hendrickson, Azevedo, and Michalek, 2016; Archsmith, Kendall, and Rapson, 2015). We use marginal generation mix estimates together with estimates of emissions for feedstock production emissions for coal and natural gas to produce a range of life cycle estimates associated with marginal electricity consumption (see Table S8).

3.2. Findings

We compute emissions across the policy scenarios using a wide range of sales projections based on data from the Energy Information Administration's 2015 Annual Energy Outlook (US Energy Information Administration, 2015) and from the California Air Resources Board as well as a wide range of assumptions for other key parameters. We find in all cases examined that fleet GHG emissions are higher for both policies together (BOTH) than for either policy alone (ZEV or AFVI). The magnitude of this increase depends on vehicle sales. Using our base case sales projections, we estimate that relative to the REF scenario (no ZEV mandate and no AFV incentives in the GHG standard), (1) adding the ZEV mandate in the presence of the GHG standard changes emissions by −16 to 61 million tons, (2) adding AFV incentives to the GHG standard increases emissions by 8–41 million tons, and (3) adding both policies together increases emissions by 17–114 million tons. Although these ranges overlap, the uncertainty for each case is correlated with the others (the same source of uncertainty affects all three estimates), and in all cases the BOTH scenario has higher emissions than the other scenarios. The largest source of uncertainty in these estimates comes from the potential for error in agency estimates of AFV upstream fuel production and distribution emissions (e.g.: electricity production emissions for plug-in vehicles), and removing that source of uncertainty substantially tightens estimates (see Fig. S4 in the SI).

Fig. 3 shows, for our base case sales projections, the change in estimated GHG emissions for passenger cars sold from 2012 through 2025 for each of the ZEV, AFVI, and BOTH policy cases relative to the REF case. In each case the stacked bars represent changes in each emission source under base assumptions; the dot is the net change in emissions (the sum of the stacked bars) under base assumptions; and the error bars represent uncertainty of the net change in emissions due to (1) uncertainty in electricity production and vehicle production emissions and their measurement by the agency, (2) uncertainty in actual on-road vehicle efficiency relative to laboratory test efficiency used for compliance calculations (represented as the difference between five-cycle and two-cycle laboratory tests), and (3) uncertainty of AFV sales induced by AFV incentives. In particular, while our sales projection data sources make sales projections in the presence of both policies and identify the portion of sales attributable to ZEV policy, they do not identify sales attributable to the GHG standard's AFV incentives. As a point estimate, we show the case where AFV sales induced by AFV incentives are half of the non-ZEV sales, and our uncertainty range captures the full range of assumptions from 0% to 100% of the non-ZEV sales. Details are provided in the supplemental information. In each case the error bars are calculated by combining all possible combinations of high and low estimates for each parameter.

- The first column shows the change in emissions for the ZEV case relative to the REF case. The ZEV mandate results in increased sales of AFVs in place of conventional vehicles, but the emissions from AFVs offset the savings from displaced conventional vehicles. The operation-related emissions cancel exactly when the agency estimates of upstream emissions are correct, and the net effect (represented by a dot) is near zero under the binding GHG standard using base assumptions (falling just above zero largely due to differences in vehicle manufacturing emissions not captured in the scope of the federal GHG standard). The uncertainty range from −16 to 61 million tons CO_2 is primarily a result of uncertainty in the potential for agency error in estimating upstream AFV emissions (if the EPA estimates upstream electric vehicle emissions as higher than they actually are, then the effective standard for the remainder of the fleet is reduced and net emissions can decrease as AFV sales increase). Fig. S4 in the supplemental information repeats Fig. 3 with the uncertainty of agency upstream AFV emissions estimation error removed, resulting in a much smaller uncertainty range entirely above zero.
- The second column shows the change in emissions for the AFVI case relative to the REF case. Adding AFV incentives relaxes the fleet GHG standard for every AFV sold. Automakers responding to this constraint relaxation sell a higher-emitting conventional vehicle fleet as a result, producing a cumulative lifetime increase of 29 [8–41] million tons of CO_2 for vehicles sold from 2012 through 2025. FFVs cause a larger effect than plug-in vehicles because of the volume sold.
- The last column shows the change in emissions for the BOTH case relative to the REF case. The ZEV mandate induces AFV sales, which displace conventional vehicle sales, but the AFV incentives relax the GHG standard for the remainder of the fleet every time an AFV is sold, so the overall standard is less stringent, and the resulting fleet is a higher-emitting fleet. The net effect is an increase in GHG emissions of 81 [17–114] million tons. This represents an average of 0.73 [0.15–1.0] tons per vehicle sold and about 2% [0.4–2.8%] of the overall GHG reductions estimated from CAFE/GHG policy.

Even under our conservative uncertainty bounds, our primary finding is robust: The combination of ZEV policy and CAFE/GHG

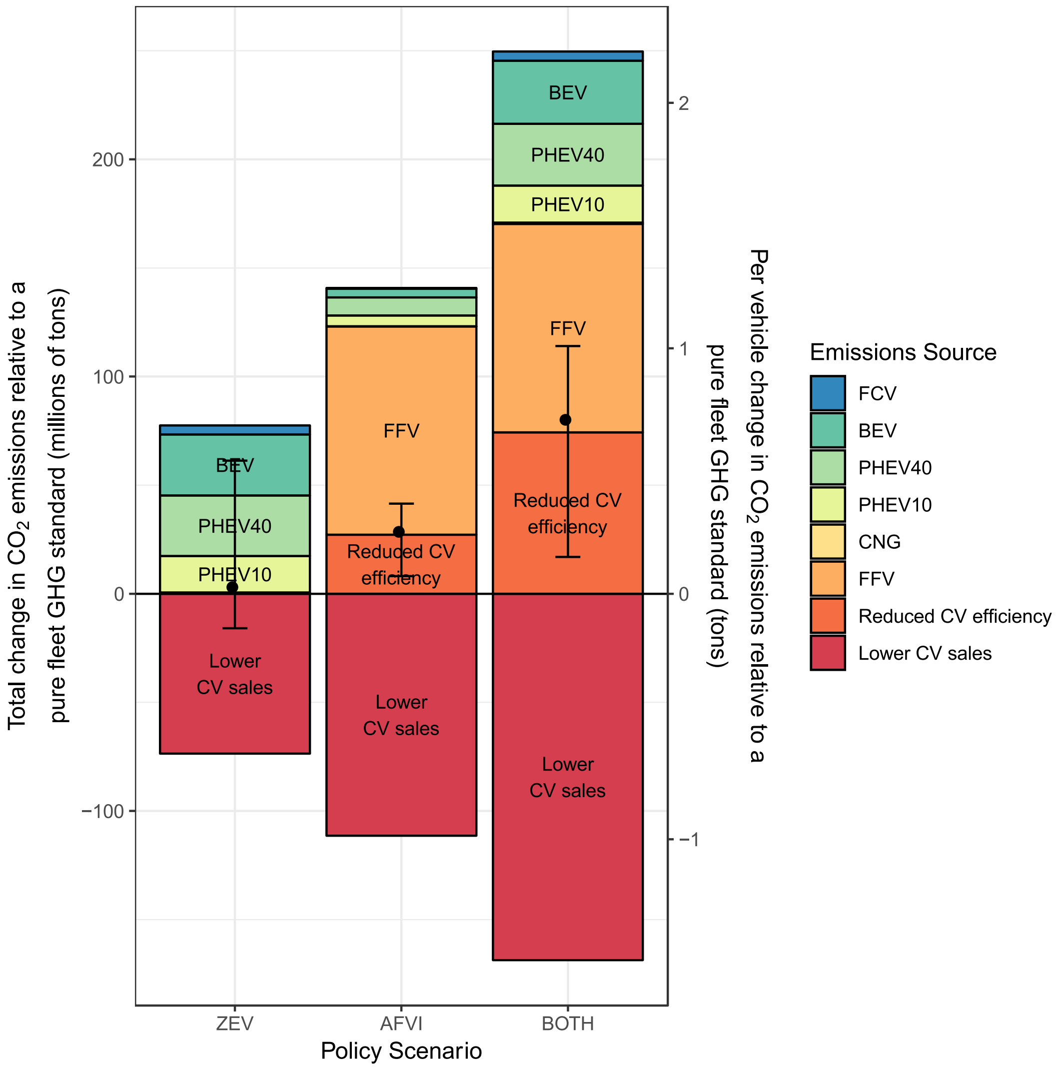

Fig. 3. Total change in life cycle emissions for the fleet of model year 2012 through 2025 passenger cars relative to a baseline scenario of pure light-duty fleet GHG standards (with no AFV incentives or mandates). AFVI refers to the AFV incentives in federal light-duty fleet GHG emission standards. Dots indicate the net change in emissions, and the error bars capture the interval of uncertainty for differences in electricity and vehicle production emissions and their measurement by the agency, on-road vs. laboratory compliance test vehicle efficiency, and AFV sales induced by AFV incentives. The secondary axis converts total change in emissions to average change per passenger car sold for scale.

AFV incentives leads to an increase in emissions relative to either policy alone.[24] In the supplemental information, we also repeat this analysis with three other sources of sales projections and observe this finding to be robust – though the magnitude of the effect depends on sales, and estimated emissions could conceivably be higher or lower if the future sales of AFVs fall outside the range of sales projections used in our sensitivity analysis.

Fig. 4 similarly shows, for the same set of sales projections and uncertainty ranges, the change in estimated gasoline consumption for passenger cars sold from 2012 through 2025 for the ZEV, AFVI, and BOTH policy cases relative to the REF case. In the first column, adding the state ZEV mandate results in a total change of −22 billion gallons of gasoline consumption when compared to the base case, as conventional vehicles are displaced by AFVs that consume less gasoline. However, the uncertainty, due primarily to uncertainty about sales induced by the AFV incentives, is relatively large: from −30 to −11 billion gallons. In the second column, adding AFV incentives increases AFV sales an uncertain amount but relaxes the fleet standard for every AFV sold. Automakers responding to this constraint relaxation sell less efficient conventional vehicles as a result, producing a net change of about −10 [−20 to +2.8] billion gallons of gasoline consumed. In the last column, the ZEV mandate forces AFV sales in place of conventional vehicle sales, and the AFV incentives relax the binding fleet GHG standard, so the remaining conventional fleet is a less efficient fleet.

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[24] The error bars are correlated because some sources of uncertainty affect all three estimates simultaneously. We separately verify that the BOTH scenario has higher emissions than the other scenarios in all combinations of values for the uncertain parameters.

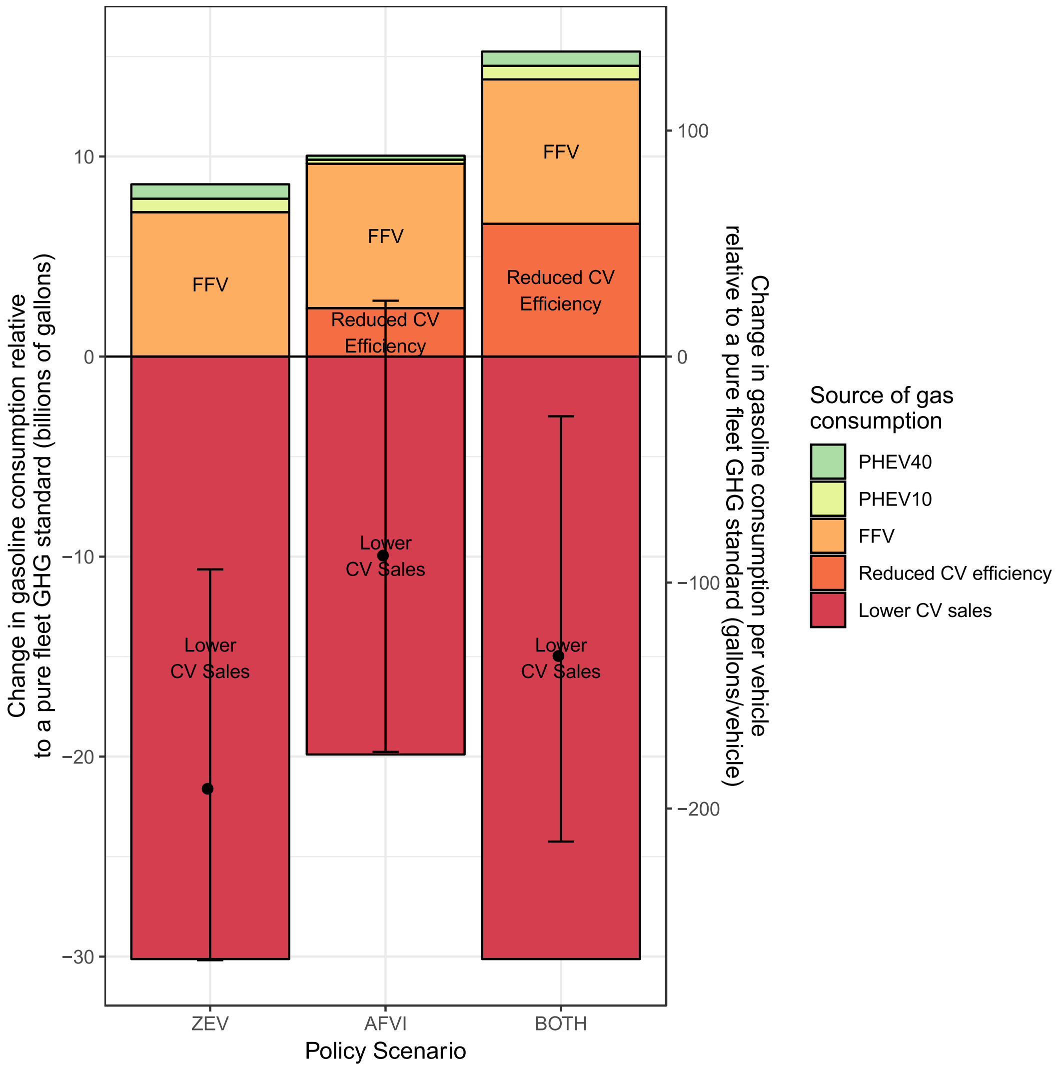

Fig. 4. Change in total gasoline consumption for the fleet of model year 2012 through 2025 passenger cars relative to a baseline scenario with pure light-duty fleet GHG standards (no AFV incentives or ZEV mandate). AFVI refers to the AFV incentives in federal light-duty fleet GHG emission standards. Dots indicate the net change in gasoline consumption, and the error bars capture the interval of uncertainty for differences in electricity and vehicle production emissions and their measurement by the agency, on-road vs. laboratory compliance test vehicle efficiency, and AFV sales induced by AFV incentives. The secondary axis converts total change in emissions to average change per passenger car sold for scale.

The effect on gasoline consumption of switching from conventional vehicles to AFVs is larger than the effect of the reduced efficiency of the remaining conventional fleet, so the net effect is a change of about −15 [−24 to −3] billion gallons of gasoline consumed from vehicles sold from 2012 to 2025. This represents −130 [−171 to −33] gallons per vehicle and about 5.5% [6.2–0.3%] of the overall gasoline consumption reductions estimated from CAFE/GHG policy during this period.

We also conduct an additional scenario extending the AFV credits in 2020 through to 2025[25] to represent a potential change to the GHG regulations proposed by the Trump administration (along with a freeze of the standards themselves). We find that with extended AFV credits, the combination of AFV policies (BOTH) results in a point estimate of 94 million tons more CO_2 than the reference case (a 13 million ton larger increase than in our base case). Details are presented in the SI Section 3.7.

4. Analysis of sufficient conditions

One potential critique of our simulation results is that, despite the wide range of sensitivity cases tested, a different set of assumptions about future fleet sales mix, vehicle emission rates, grid emission rates, or other factors could lead to a different finding.

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[25] Federal Register Vol. 83, No. 165 "The Safer Affordable Fuel-Efficient Vehicles Rule for Model Years 2021–2026 Passenger Cars and Light Trucks". pp. 43461.

To further characterize the robustness of our results, we identify a set of assumptions sufficient to prove that GHG emissions are higher in the BOTH policy scenario than in the ZEV or AFVI scenarios alone. To do this, we apply Eq. (5) to the four policy scenarios in Fig. 2 and write expressions for the differences between scenarios (see SI Section 2). We examine the resulting equations and identify a set of conditions under which the net emissions in the BOTH scenario are larger than in the ZEV, AFVI, and REF scenarios. The conditions are:

(1) **Incentives Increase Sales:** ZEV policy and AFV incentives each increase sales of at least some AFVs and do not reduce sales of any AFVs;
(2) **AFV Operation Emissions:** AFVs have lower use-phase emissions than the fleet average vehicle;
(3) **AFV Production Emissions:** AFV production emissions are comparable to or potentially higher than conventional vehicle production emissions, and
(4) **Agency Grid Emissions Estimates:** agency estimates of upstream fuel production emissions are accurate or potentially optimistic.

In the Supplemental Information, we summarize evidence that each of these conditions holds in practice. The identified conditions are sufficient to show that GHG emissions are larger in the BOTH scenario than in the other scenarios, but they are not necessary – i.e.: there exist more general conditions under which our conclusions hold, but the stated conditions are sufficient and easy to understand. Some degree of violation of these conditions can be tolerated without changing our conclusions. Mathematical details are provided in the Supplemental Information.

Under these conditions, we identify three findings:

Finding 1: ZEV policy increases emissions. Adding ZEV policy to a pure GHG standard results in higher emissions than under the pure GHG standard alone.
Finding 2: AFV incentives increase emissions. Adding AFV incentives to a pure GHG standard results in higher emissions than under the pure GHG standard alone.
Finding 3: Combining policies increases emissions. The combined effect of ZEV policy and AFV incentives together results in higher GHG emissions than under the ZEV policy alone or the AFVI policy alone.

As described previously, our model assumes that the automotive industry sells the highest-emitting fleet permitted (in order to obtain other things like lower cost or higher performance), and the policy changes examined do not induce changes to automakers' GHG standards (other than the AFV incentives themselves), such as causing changes in vehicle footprint. In the Supplemental Information we summarize evidence that this assumption holds. Additionally, our model also assumes fixed VMT per vehicle across the fleet, and our model assumes that while the policies in question may affect vehicle design or sales mix, they do not affect the total number of new vehicles sold. While total new vehicle sales could potentially be affected by these AFV policies in practice (Jacobsen and Benthem, 2015), it is difficult to credibly model net emissions implications from changes in new vehicle sales without also modeling induced changes in the used car market, transit, and other sectors, introducing substantial uncertainty. Instead, we conduct sensitivity analysis to observe how much total new vehicle sales could change without altering our qualitative results for the new car fleet, and we find that our key finding holds if the combined policies (BOTH) do not reduce new vehicle sales by more than 1% relative to sales under either policy alone (ZEV or AFVI) (see SI Section 3).

5. Discussion

We find that in the presence of federal fleet GHG standards, interactions between federal and state AFV adoption policies lead to increased fleet greenhouse gas emissions relative to either AFV policy alone. The primary goal of federal light-duty GHG standards is to reduce near-term GHG emissions from the fleet, and prior analysis shows that it accomplishes this goal, albeit inefficiently. In contrast, the primary goal of both state ZEV policy and of federal AFV incentives in the GHG standards is to develop a market for AFVs and help enable a long-term fleet technology transition. We show that pure GHG standards (without AFV incentives) together with ZEV policy can potentially make progress toward these individual goals without a negative influence on one another. However, the AFV incentives in federal GHG standards, which allow automakers that sell AFVs to meet less stringent fleet emissions standards, produce net increases in fleet emissions that are compounded under ZEV policy. While state ZEV policy and federal GHG AFV incentives are both intended to encourage AFV sales and spur technology development and market acceptance toward a long-term fleet transition, the ZEV policy can potentially achieve this goal without significant increases to near-term GHG emissions, whereas the AFV incentives increase net GHG emissions, and the combination of the two policies further increases net emissions. If the goals of the federal and state policy are to reduce GHG emissions and gasoline consumption while encouraging AFV sales, the policies would produce better outcomes if AFV incentives were removed from GHG standards, decoupling the two goals and allowing ZEV objectives to be pursued without a significant effect on GHG goals. Of course, other factors, such as the effect of more stringent GHG standards on industry and employment, implications for congestion or conventional air pollution, effects of innovation and technology development, and effects on the used car market should be considered as well when making such policy decisions (Parry et al., 2007). The different jurisdictions and regulatory authorities under which these policies are currently implemented also poses challenges for policy coordination. As long as the AFV incentives for the federal GHG standard are in place (planned at least through 2025), states considering adopting California's ZEV program should consider the effect that federal and state policy interactions will have on U.S. fleet emissions and gasoline consumption.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tra.2019.04.003.

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